16th Annual
Advanced Space Propulsion Workshop

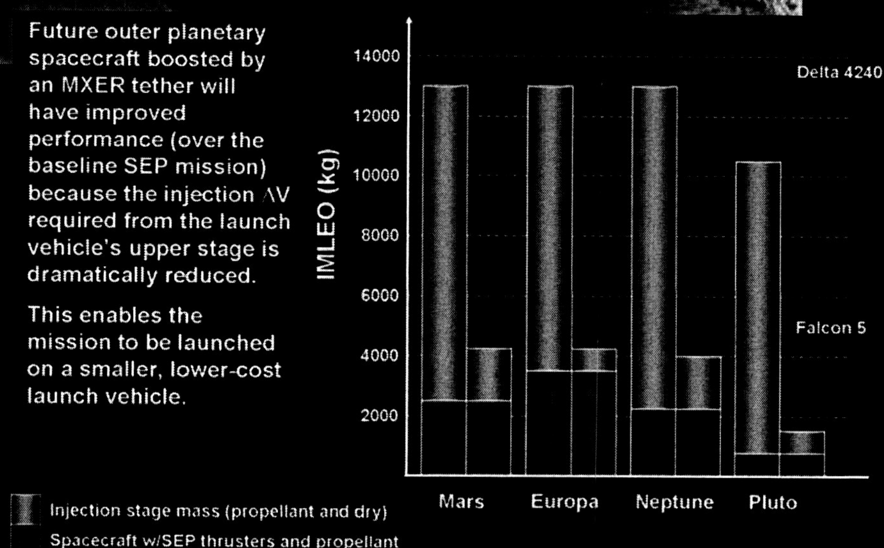
Tether Technologies for Future Space Applications

Mr. Kyle L. Frame
Mr. John W. Dankanich
Dr. Joseph A. Bonometti

Emerging Propulsion Technologies
NASA, Marshall Space Flight Center

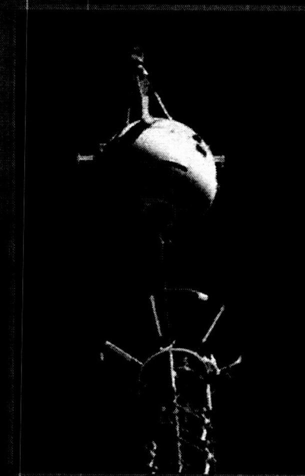
Future outer planetary spacecraft boosted by an MXER tether will have improved performance (over the baseline SEP mission) because the injection ΔV required from the launch vehicle's upper stage is dramatically reduced.

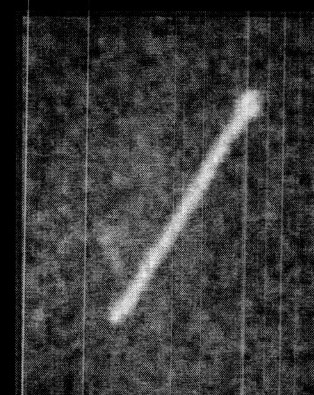
This enables the mission to be launched on a smaller, lower-cost launch vehicle.



Tether Technology Flight Heritage

- **More than sixteen tether missions have flown since 1967.**
- **Some of the most recent missions have demonstrated various capabilities:**
  - TSS-1 (July 1992)
    - Successful Initial Deployment and Dynamic Stability
    - Recovery from Dynamic Upsets & Slack Tether
    - Near retrieval (most critical aspect) from 276 m was nominal
  - SEDS-1 (March 1993)
    - Successful deployment of a 20-km non-conductive tether
    - Demonstrated intentional severing of tether
  - PMG (June 1993)
    - Successful deployment and bi-directional ED operation using 500 m conducive tether
    - Max current of 300 mA
  - SEDS-2 (March 1994)
    - Successful deployment of a 20-km non-conductive tether
    - Attached tether stabilized in vertical position
  - TSS-1R (February 1996)
    - Successful deployment of 19.7 km out of 20 km (conductive) tether
    - Demonstrated superior current collection
    - Generated power (3.5 kV), current (480 mA) and demonstrated thrust
    - Demonstrated safe orbital separation
  - TiPS (June 1996)
    - Tether designed to expand slightly after deployment
    - Successful deployment of 4 km of non-conducting tether
    - Deployed into 1000-km orbit (high-debris region) and still intact (no sever)





NASA

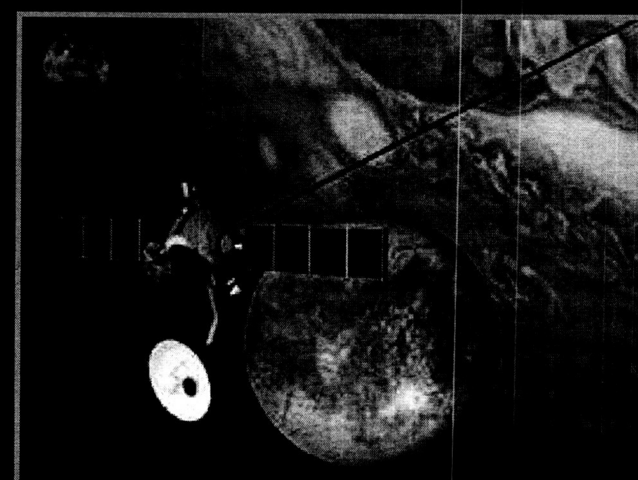
Tether Applications

Mechanical Tethers
- Momentum Exchange
- Artificial Gravity
- Forced Over-speed Orbits
- Transmitters
- Payload Deployment and Retrieval
- Science sampling (atmospheric and surface)
- Formation flying
- Gravity gradient

ED Tethers
- Re-boost
- De-orbit
- Power Generation
- ED capture at numerous planets
- ED tug
- Radiation remediation

MXER
- Payload Delivery to and from the Moon
- Lunar ascent/descent
- Mars transportation
- Interplanetary robotic missions
- Commercial and military GEO satellites

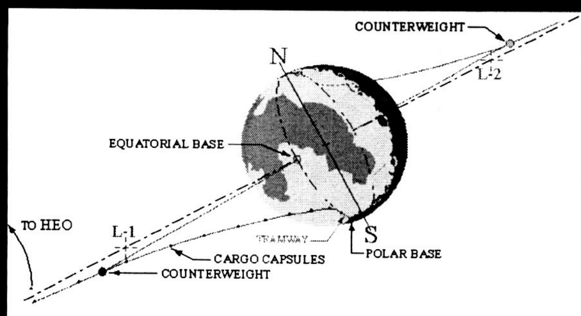
Synergistic Technologies
- Rotating Joint
- Radiation Hardening
- Inflatable Structures
- FEAC Development
- Spacecraft Design
- Long Life Components
- Science of Debris/Space-Particle Environment
- Multi-satellite Formation Flying Precision Control
- Power Storage
- Non-Keplarian Trajectory Algorithms
- Materials Manufacturing and Development
- Conducting Polymer Research
- Neural Network Prediction Code
- Spacecraft Propagation Tracking



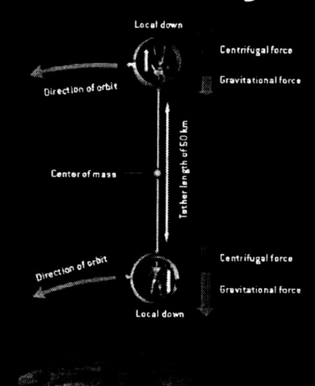
Mechanical Tethers

- Safety

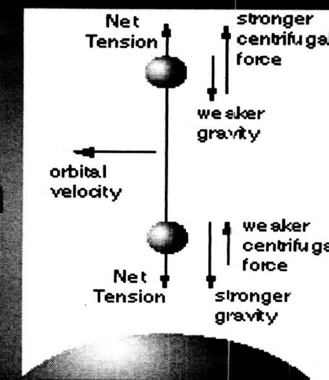
- Lunar Elevators



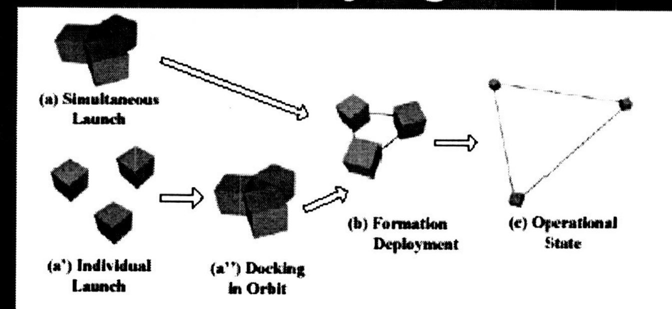
- Artificial Gravity



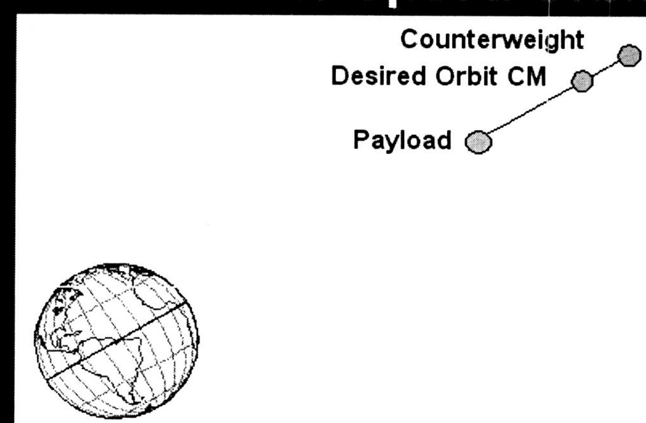
- Gravity Gradient Stabilization



- Formation Flying

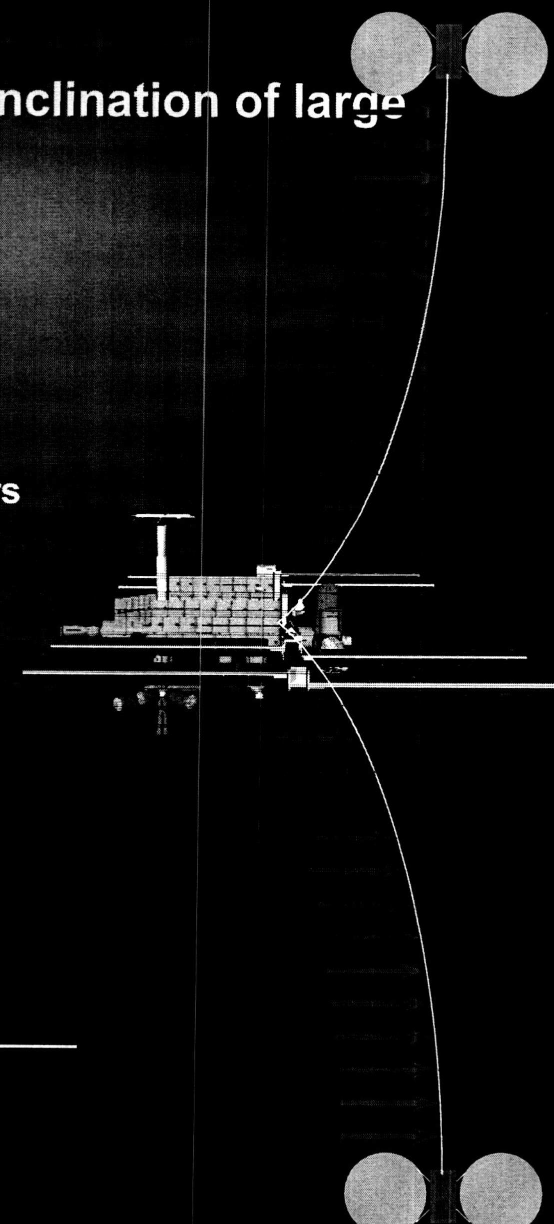


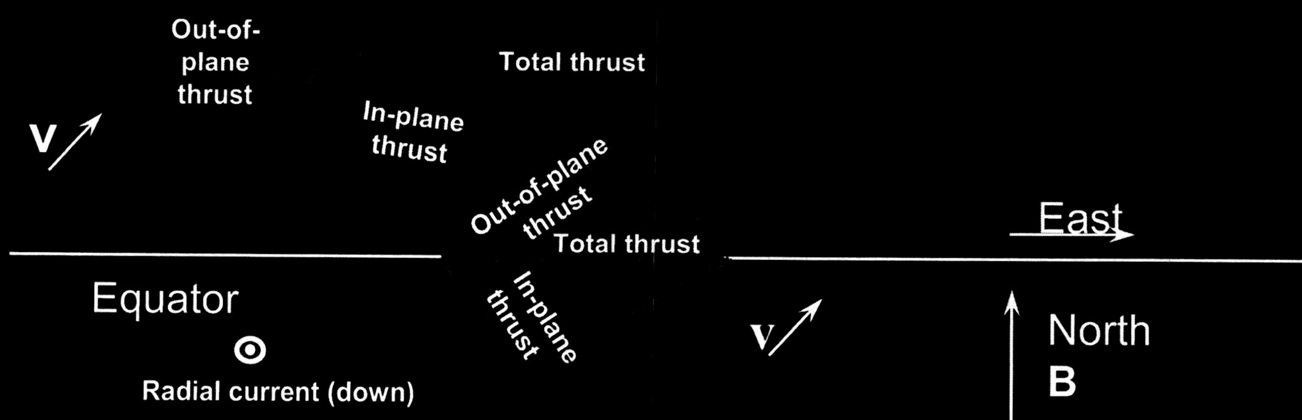
- Forced Over-Speed Orbits



Electrodynamic (ED) Tethers

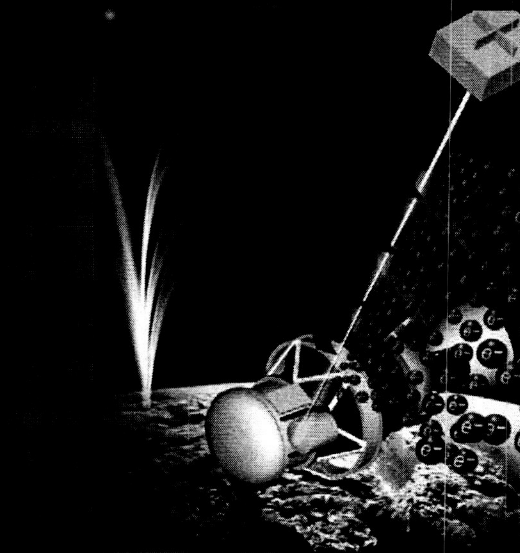
- **Capable of de-orbiting, reboosting, or changing the inclination of large U.S. assets without the consumption of propellant**
  - **De-orbiting space debris or dead satellites**
  - **ISS requires 5-7 km tether with 20-30 A of current for re-boost**
    - Can save ~$100M / year compared to bi-prop costs currently used
  - **Lower ISS inclination from 51.5⁰ to 28.5⁰ over period of four years**
    - Requires a 50-km tether
    - 30-40 A of current
    - Lox LH2 would require 300 MT of Propellant



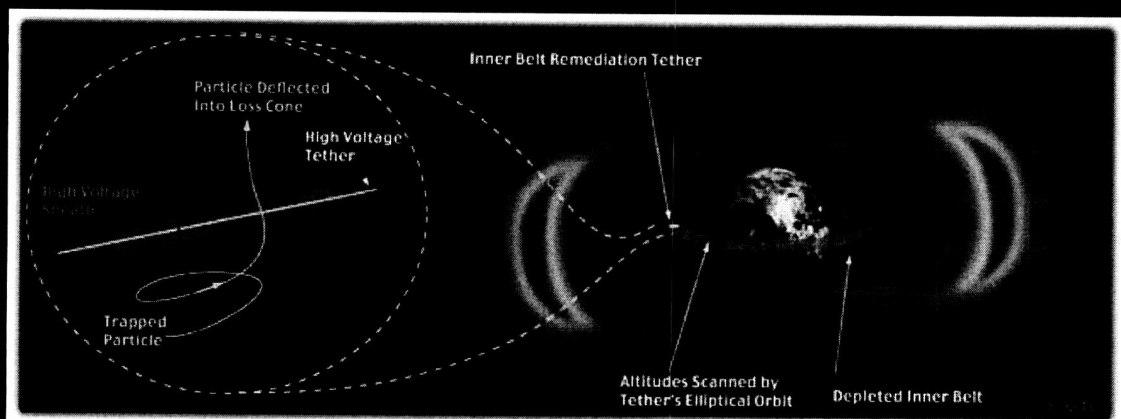


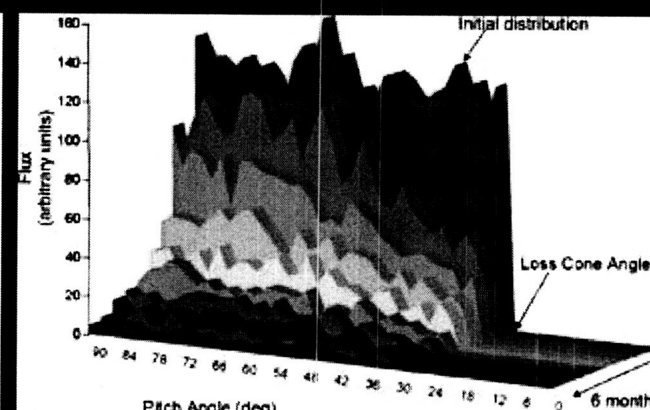
ED Tethers Cont.

- **Electrical Current in the Tether**
  - Electrical power produces thrust
  - Drag can generate electrical power



- **Radiation Remission (electrostatic)**

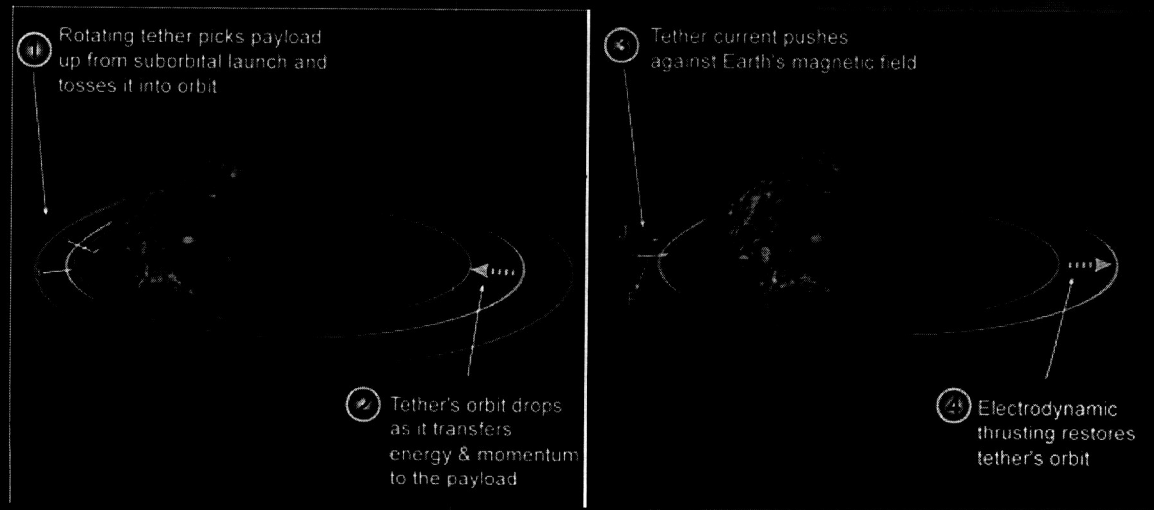




Van Allen Radiation may be reduced to <1% within 6 months.

Momentum-Exchange (ME) Tethers

- GTO



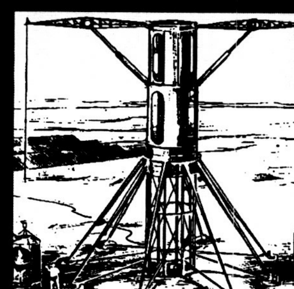
- Cis-Lunar

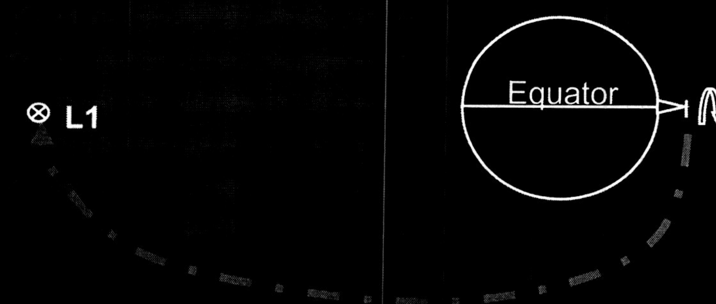
- Payload is thrown from LEO to TLI
- Second tether can catch payload and place on lunar surface
- Additional infrastructure can return mass and energy

Future "Lowering The Cost" Options

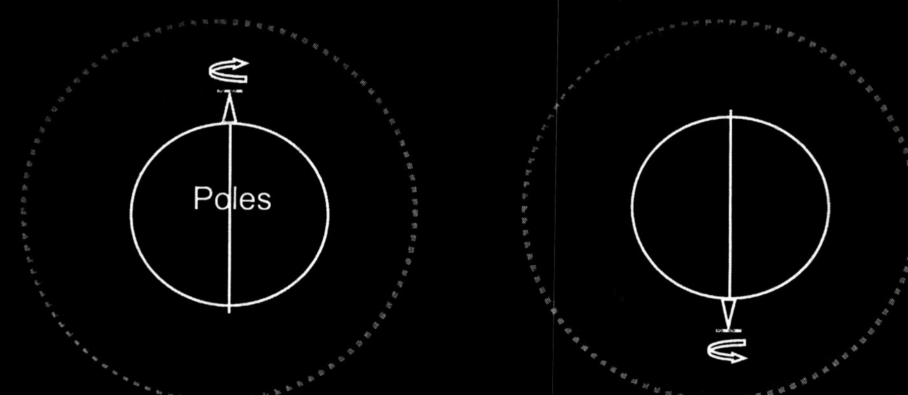
- ' Lun-a-vator' or space elevator for the moon using an asteroid

- Moon Surface Slingshot on equator





- Surface slingshot on the two poles of the moon



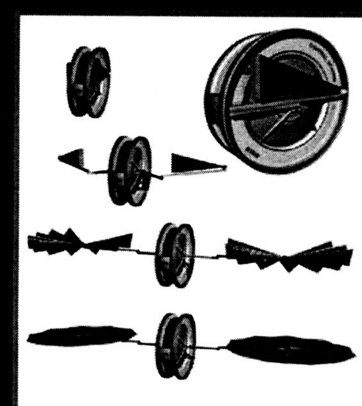
- Tethers at Mars and on Phobos

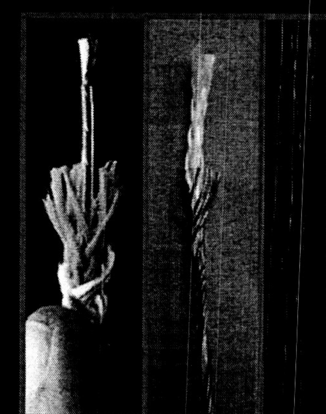
Momentum eXchange Electrodynamic Reboost (MXER) Tether

- **The MXER Tether is a reusable, "propellantless", in-space "upper stage" for sending payloads from LEO to GTO and beyond.**
  - Long, rotating cable operating in an elliptical orbit.
  - Restores orbital energy by using electrodynamic tether
  - Development time: 10-15 years

- **Potential benefits to payloads using MXER**
  - Increase in Isp while maintaining reasonable trip time
  - Lowers overall mission cost and/or enables larger payloads
  - Capable of ~75% Earth escape Delta-V
  - Interplanetary mission enhancer
  - Useable by essentially all missions beyond LEO
  - A spiral development for future generations
    - Readily scales up or down
    - Future transportation to and from Lunar surface

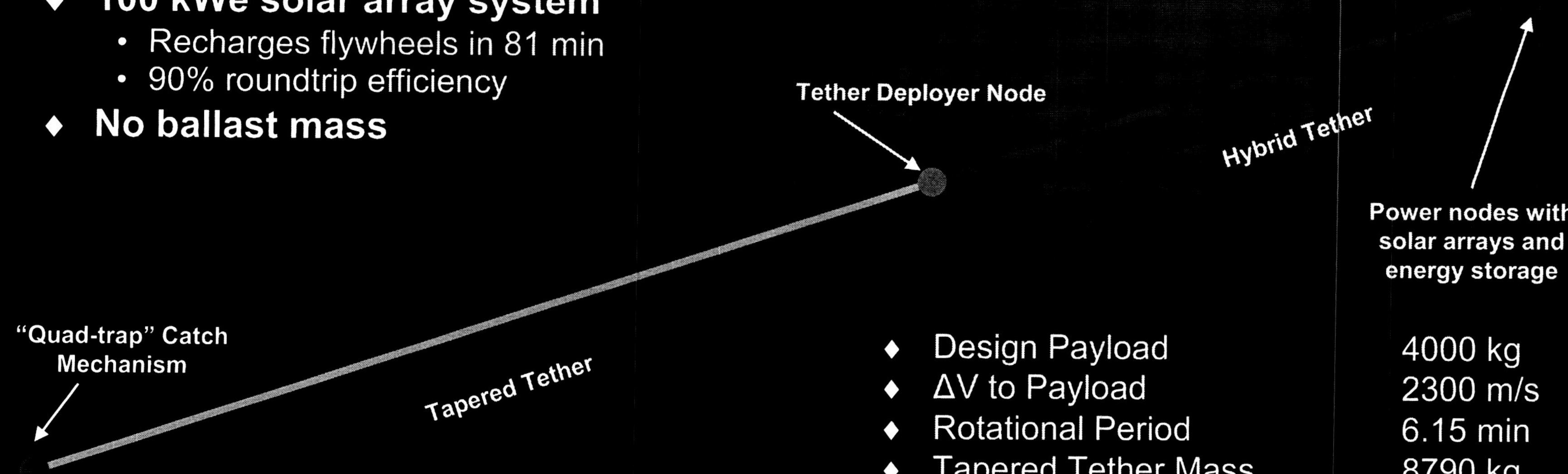
- **Allowable launch vehicles savings by using MXER**
  - Increase in payload size and capability
  - Savings provided by MXER used on more missions
  - Expense saved without long duration in radiation belts





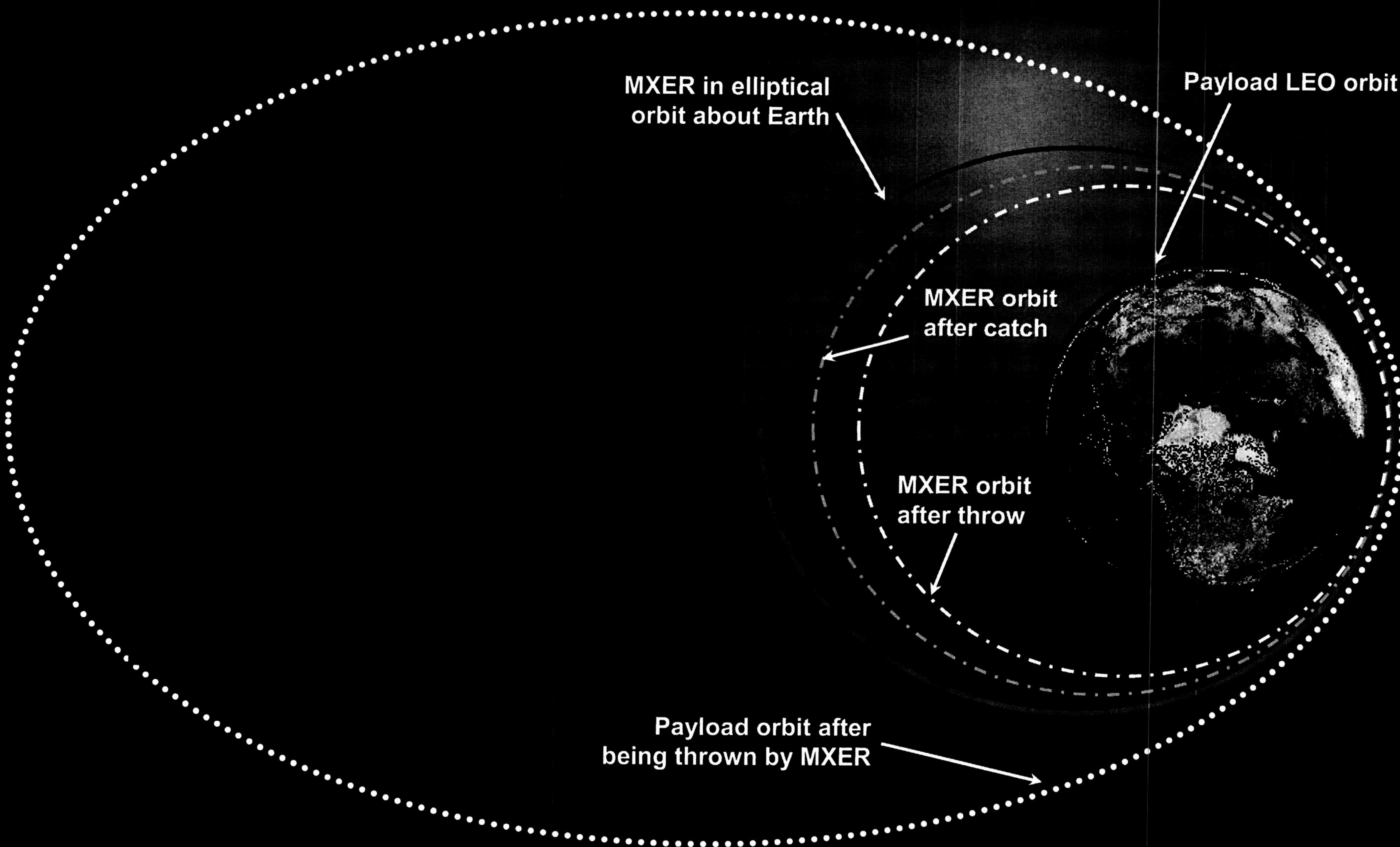
Single Delta-4H Launch MXER Tether Facility (typical point design)

- **116.5-km long tether**
- **Single 500-kg deployer node**
  - 49-km Zylon-aluminum hybrid tether
  - 67.5-km Zylon tapered tether
- **Six 1000-kg power nodes, each with**
  - 23.5 kW*hr G3-class flywheel
  - 20 kW*hr usable energy
  - 85% depth-of-discharge
- **100 kWe solar array system**
  - Recharges flywheels in 81 min
  - 90% roundtrip efficiency
- **No ballast mass**

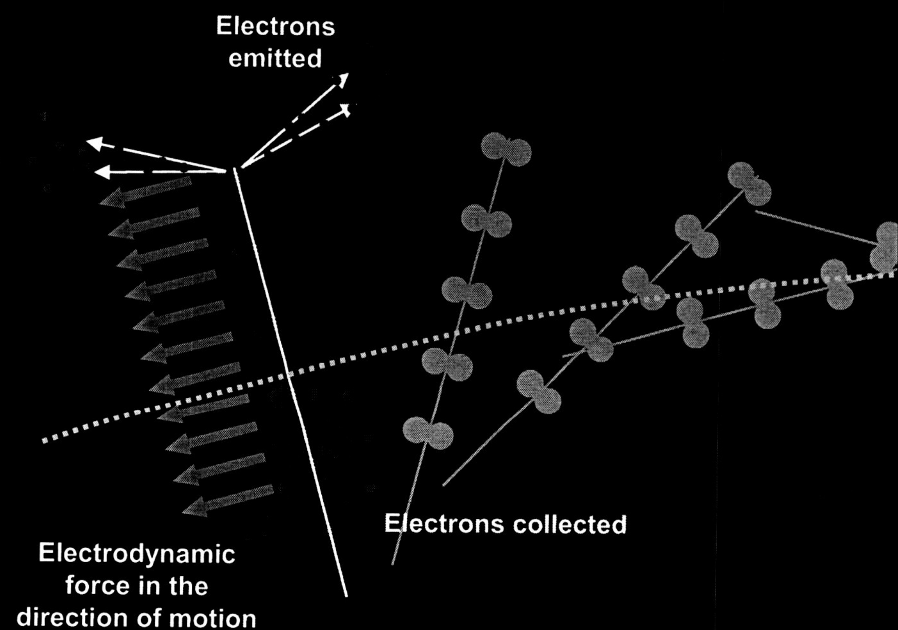


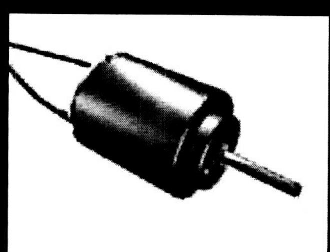
Design Payload	4000 kg
ΔV to Payload	2300 m/s
Rotational Period	6.15 min
Tapered Tether Mass	8790 kg
Hybrid Tether Mass	6890 kg
Aluminum Mass	3000 kg
Total Facility Mass	22580 kg
Launch Vehicle Margin	9.7%
Estimated Reboost Time	*32 days*

MXER Tether Propulsion



Space Tethers





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MXER Tether Benefits for Outer Planets Missions

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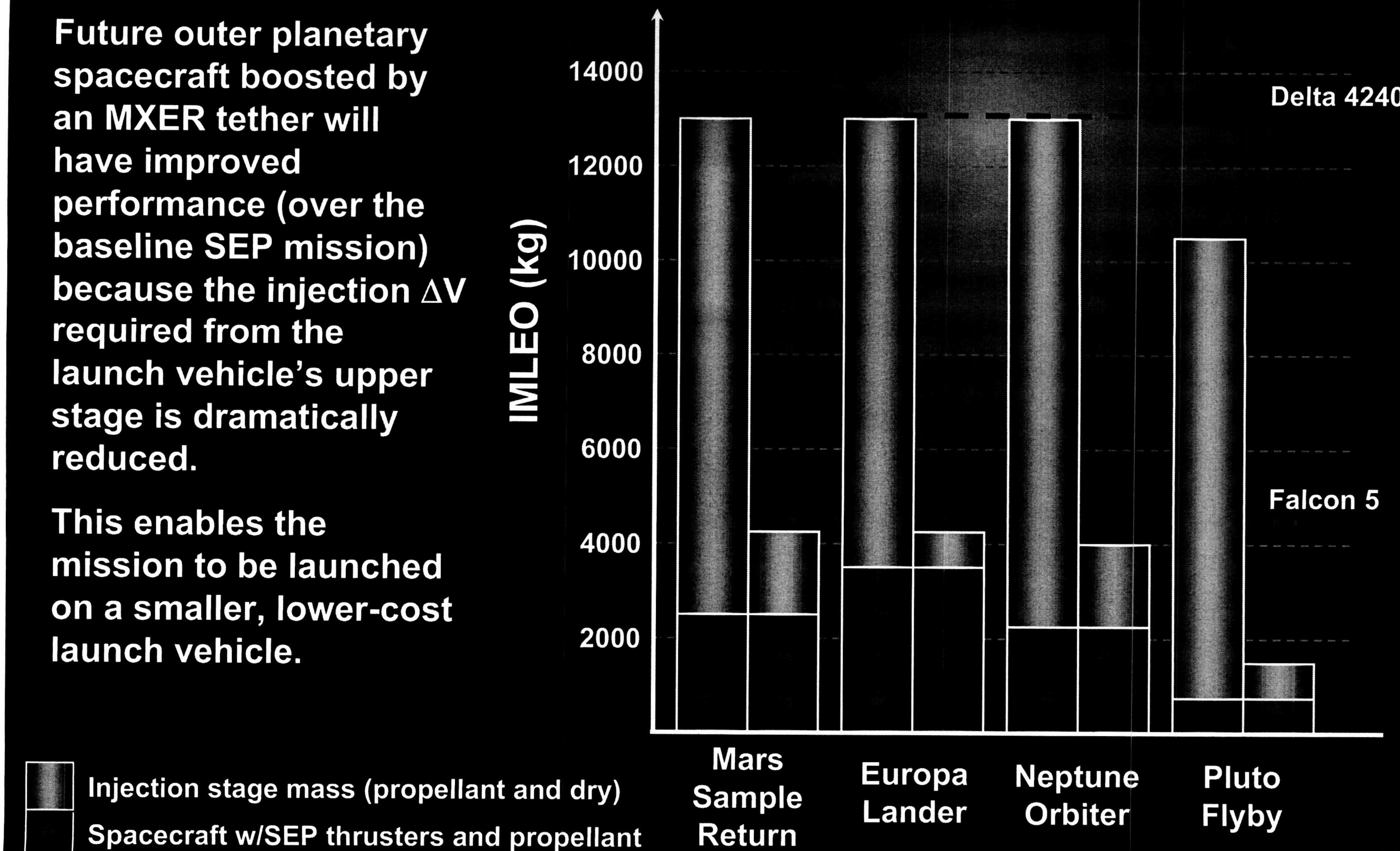
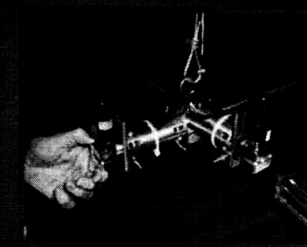
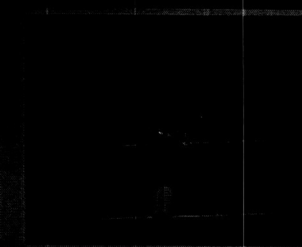


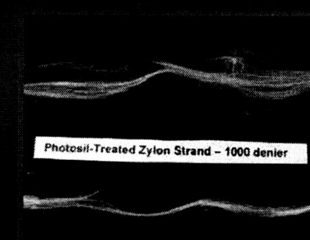
Progress on MXER Subsystems

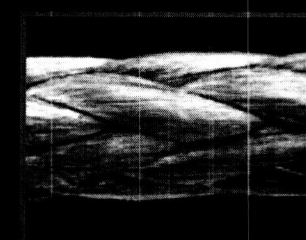
- **Catch Mechanism**
  - More than 30 capture concepts proposed and initially analyzed
  - Four concepts selected for Phase II analysis
  - Quad-Trap Catch Mechanism was designed and manufactured (breadboard)
  - Testing has produced a successful catch better than 95%



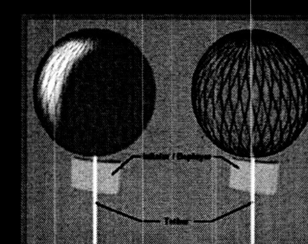


- **Propagator/Predictor Code**
  - Numerous initial models incorporated into design code
  - Preliminary results predict an accuracy within 1-m (one orbit prior to catch)
  - Alpha version of propagator code due completion in Spring 2005
- **Strength Tether**
  - Received numerous tether samples
  - Performed independent, preliminary testing on supplied samples
    - Atomic Oxygen
    - Ultraviolet radiation
    - Tensile strength
  - Additional set of samples to be tested





- **Electrodynamic Tether Material**
  - Currently analyzing multiple coating processes on polymers
- **Plasma Contactors**
  - Initial analysis performed to evaluate use of anode concepts
    - Bare wire anode
    - Grid-sphere anode
  - Testing of Field Emitter Array Cathodes (FEAC) in MXER environment near complete
  - Alternative method for ED operations without using plasma contactors is being analyzed

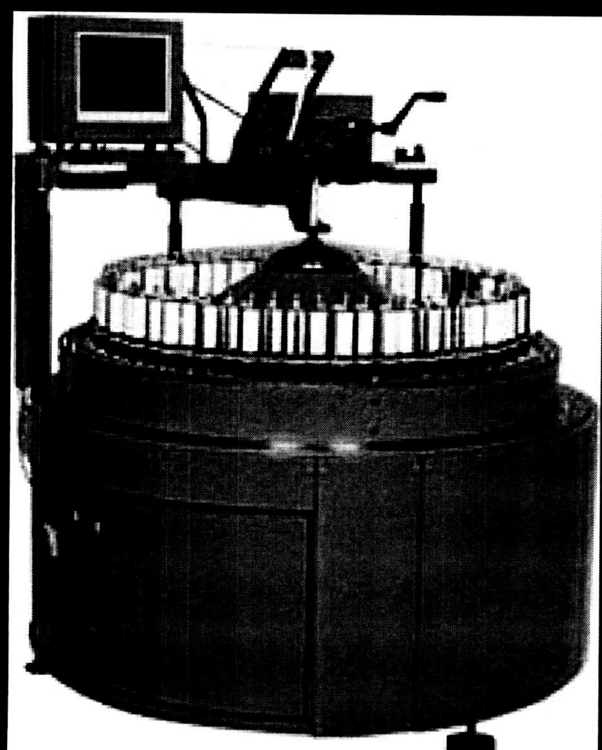


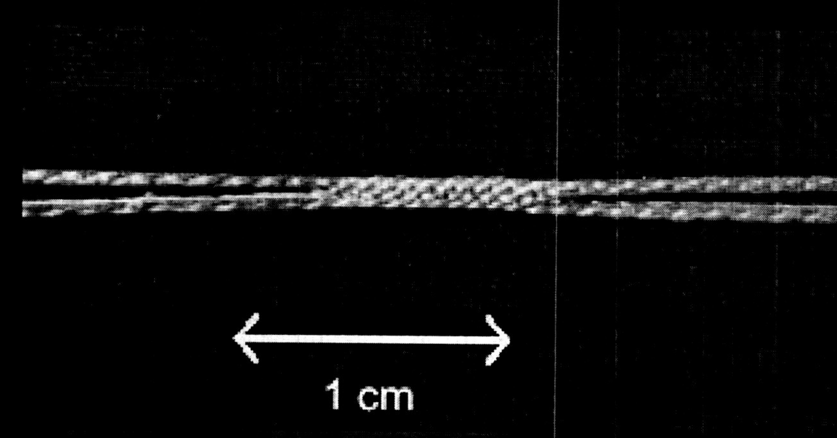
Catch Mechanism Testing

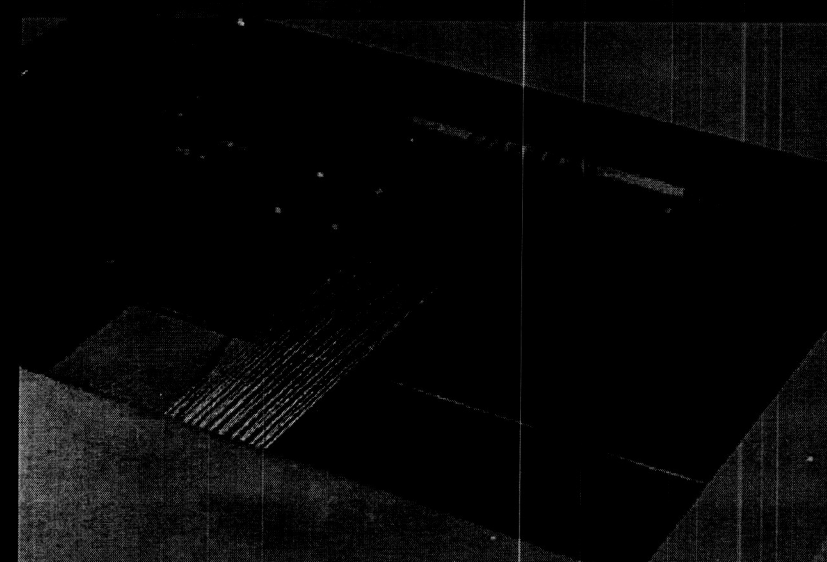
Backup Slides

Manufacturing and Testing Space Tethers

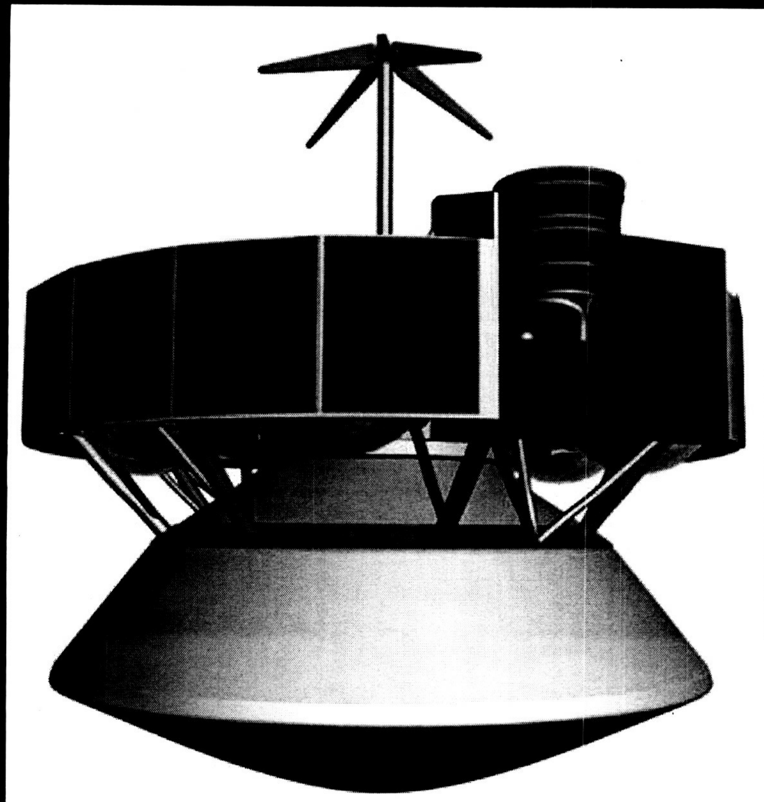
Hoyt tether structure- break will not degrade strength



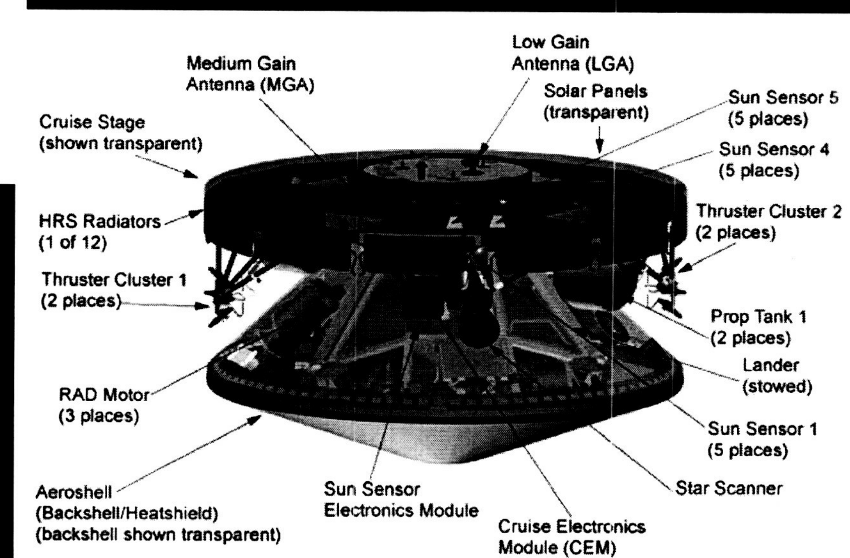




Mars Rover Cruise Stage Comparison



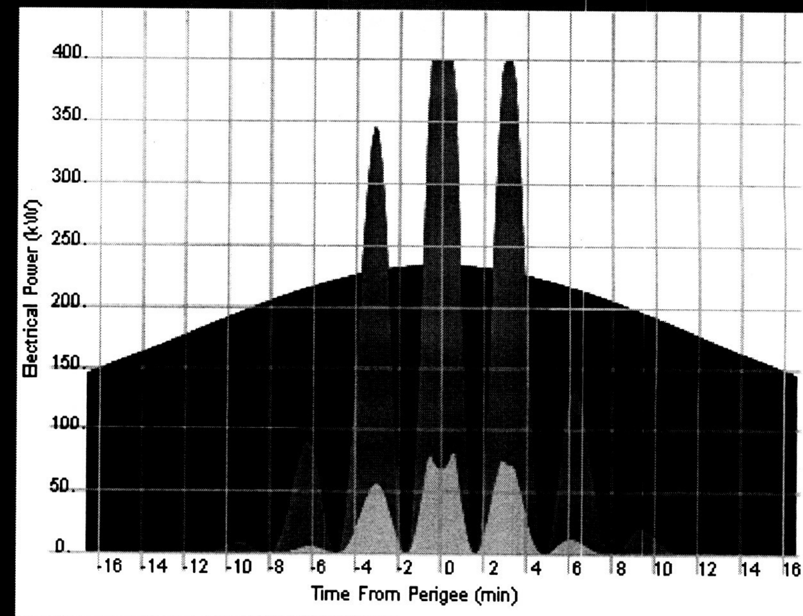
- The MXER payload injection stage is similar in concept to the Mars Exploration Rover cruise stage, but with significantly more propellant, engine power, and tether capture hardware.



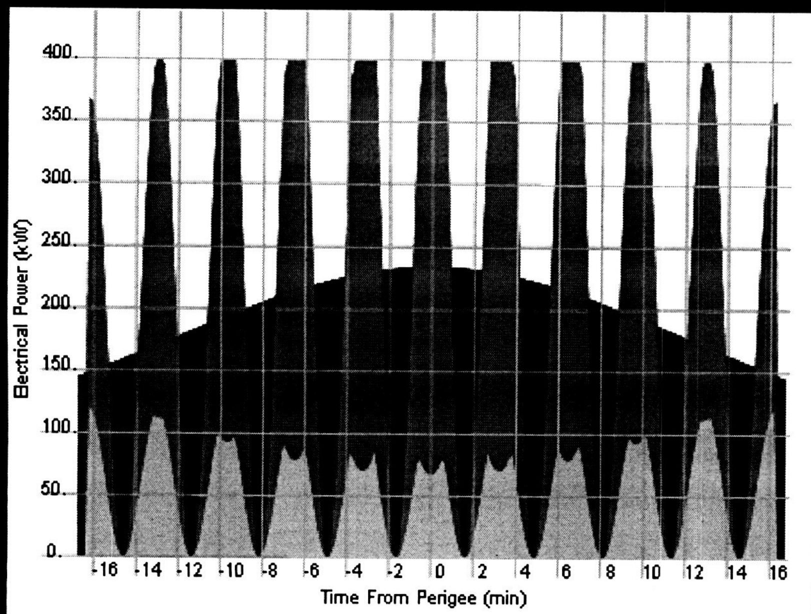
Advances in MXER Electrodynamic Reboost

- Electrodynamic reboost modeling has been incorporated into the MSFC MXER tether design tool.
- Results indicate that electrical current collected from the ionosphere lead to an attractive MXER design, due to the elliptical orbit of the tether and huge variations in free electron density.

Conventional reboost approach: 86.8 days



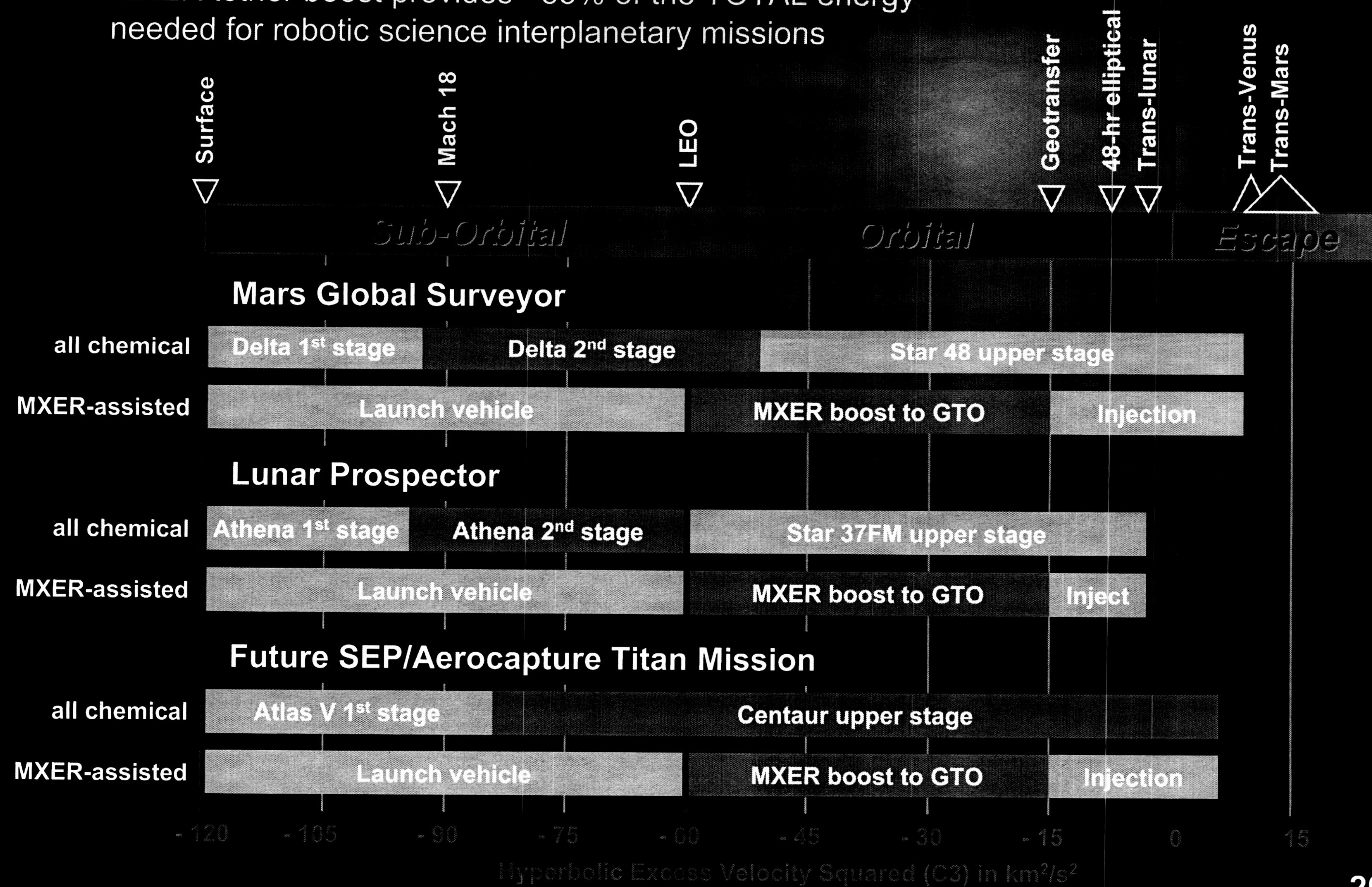
Alternative reboost approach: 31.8 days



- Electrical current generated through ionization (as suggested by Dr. Nobie Stone) has been modeled and shown to lead to ED reboost times of < 1 month.
- The feasibility of this approach is under active investigation but preliminary analyses point to its feasibility.

Energy Needed for Interplanetary Missions

- MXER tether boost provides ~35% of the TOTAL energy needed for robotic science interplanetary missions



Potential Uses of MXER Tethers

- **NASA robotic science missions**
  - Discovery missions (Delta II-class interplanetary)
  - Mars Exploration Program missions
  - Solar System Exploration missions (Titan/Neptune)
  - Sun-Earth Connection missions to GEO, E-S L1, and Earth-trailing orbits
  - Most payloads are 1000-4000 kg.

- **GEO satellites**
  - Most GEO satellites are 3000-5000 kg

- **Human lunar and Mars exploration**
  - Early MXER facilities could supply propellant and small payloads to an L1 "Gateway".
  - Larger MXER facilities could send human missions to the Moon or L1.
  - The ONLY high-thrust, infinite-Isp option available.